Ciência Rural, Santa Maria, v.54:12, e20230472, 2024 http://doi.org/10.1590/0103-8478cr20230472
ISSNe 1678-4596
SOIL SCIENCE

Soil C stocks in latossolos of the planalto, Rio Grande do Sul, Brazil

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ABSTRACT: Approximately 5% of the total emissions (0.11 Gt CO_2 and GWP-AR5) originate in Rio Grande do Sul state (RS), a representative agricultural region in Southern Brazil. This study assessed SOCS (soil organic C stocks) in Latossolos of the Planalto of RS, with up-to-date data obtained from recent field campaigns and legacy data, and relate these SOC stocks to environmental variables. A literature search identified 195 documents with SOCS in layers 0-30 cm and 0-100 cm. The mean SOCS (0-30 cm) in the Latossolos was significantly higher (73.6 Mg ha^{-1}) than the suggested IPCC default (55 Mg ha^{-1}). The highest stocks (237 ± 39 Mg ha^{-1}) were measured in uncultivated Latossolos Brunos in the 0-100 cm layer, especially at higher altitudes and lower mean annual temperature. The most frequently occurring soil Latossolo Vermelho distroférrico-LVdf (25% of the Planalto), also had high SOCS. Surprisingly Latossolos Vermelho Distrófico (LVd) also had high SOCS, in spite of the coarser texture. The estimated SOCS in Latosoolos of the Planalto is 419.9 Tg C, 36% larger than reported previous studies. We concluded that, despite significant land use changes, soils of this region maintain large SOCS which had been underestimated in previous studies.
Key words: soil management, climate change, greenhouse gas inventories, ecosystem services.

Estoques de C em Latossolos no planalto, Rio Grande do Sul, Brasil

RESUMO: Aproximadamente 5% das emissões totais (0,11 Gt CO_2 e GWP-AR5) têm origem no Rio Grande do Sul (RS), região agrícola representativa do Sul do Brasil. Este trabalho teve como objetivo avaliar os estoques de SOCS (estoques de C orgânico do solo) em Latossolos do Planalto do RS, com dados atualizados obtidos de campanhas de campo recentes e dados legados, e relacionar esses estoques de SOC com variáveis ambientais. Uma busca na literatura identificou 195 documentos com SOCS nas camadas de 0-30 cm e 0-100 cm. A média de SOCS (0-30 cm) nos Latossolos foi significativamente maior (73,6 Mg ha^{-1}) do que o padrão sugerido pelo IPCC (55 Mg ha^{-1}). Os maiores estoques (237 ± 39 Mg ha^{-1}) foram medidos em Latossolos Brunos não cultivados, na camada de 0-100 cm. O solo Latossolo Vermelho distroférrico-LVdf (25% do Planalto), mais frequente, também apresentou SOCS elevado. Surpreendentemente, o Latossolos Vermelho Distrófico (LVd) também apresentou SOCS elevado, apesar da textura mais grossa. O SOCS estimado em Latossolos do Planalto é de 419,9 Tg C, 36% maior do que estudos prévios relatados. Concluímos que, apesar das mudanças significativas no uso da terra, os solos dessa região mantêm grandes SOCS que haviam sido subestimados em estudos anteriores.
Palavras-chave: manejo do solo, mudanças climáticas, inventários de gases de efeito estufa, serviços ecossistêmicos.

INTRODUCTION

Agriculture is responsible for a large part of greenhouse gas (GHG) emisisons in Brasil: 2.4 Gt CO_2, with 0.11 Gt CO_2 e GWP-AR5 originating in RS state (approximately 5% of the total) (SEEG, 2023). In this context, estimates of soil organic carbon stocks (SOCS) provide crucial information for the National Communications that have been submitted to the United Nations Framework Convention on Climate Change (UNFCCC) (UNFCCC, 2020).

The predomintant soils in the Planalto of the RS – one of the most impotant grain-porducing area in Brazil – are deep, clayey Latossolos (Oxisols). Because of their fine texture, these soils store large amounts of organic C and have the potential to accumulate additional C (BAYER et al., 2000; DICK et al., 2009; FERREIRA et al., 2016). Detailed and up-to-date information on SOCS status has rarely been assessed or surveyed in Brazil, especially as outlined in the Guidelines for the National Inventories (IPCC, 2006; 2019): using reference soil depths (0-30 or 0-100 cm) and stratified by soil classes and land use and land cover (LULC).

An alternative approach to bypass these shortcomings would be SOCS inventory estimation based on secondary (or legacy) data obtained from published studies and/or soil databases. BERNOUX et al. (2002) mapped the “original” SOCS in Brazil, prior to anthropic land use conversion. These SOCS

Received 08.30.23 Approved 04.05.24 Returned by the author 06.26.24
CR-2023-0472.R1
Editor: Leandro Souza da Silva

have also been called “no land use” (SANDERMAN et al., 2017) or Projected Natural Vegetation Soil Carbon (WARING et al., 2014). More recently, digital soil mapping approaches were applied to obtain country-wide SOCS using data from soil profiles obtained from databases (FIDALGO at al., 2012; MAPBIOMAS, 2023). Refined, harmonized and easily accessible SOCS data are crucial to assess and monitor cropland dynamics and agricultural practices, to inform public entities for the National Greenhouse Gas Inventory, and support environmental and agricultural policy such as the ABC Plan (ASSAD et al., 2020).

The objectives of our study were: a) to assess SOCS in Latossolos (Oxisols) 0of the Planalto of Rio Grande do Sul (RS) with data obtained from field campaigns and a literature search; b) evaluate interrealationships of SOC stocks with environmental variables.

MATERIALS AND METHODS

Base data

This research focused on the Latossolos (Oxisols) of the Planalto Sul-Rio-Grandense region (Rio Grande do Sul Plateau, hereafter Planalto), located withih coordinates 27°10’ and 29°30’S and 49°40’ and 56°50’ W, comprising 10.7 Mha (Figure 1). The Planalto is a key grain producing region of Brazil with large areas dedicated to soybeans, corn and wheat (IBGE, 2023). Before settlement, land cover was mostly woodlands (Atlantic Forest) and grasslands (Campos), the latter including a section of the Brazilian Pampa biome (VERDUM et al., 2019; TORNQUIST et al., 2024). Most of these lands were converted to cropland of the in the early 1900s (TORNQUIST et al., 2009). The MapBiomas Project (AZEVEDO et al., 2023) reported that in 2021 more than 50% of the Planalto under cropland (Figure 1) The major soil class is Latossolos Vermelhos (Oxisols) (4.5 Mha) and Neossolo Litólico (1.3 Mha) and Nitossolo Vermelho (1.4Mha). We present soils and their distribuition classified at the suborder level of the SiBCS – Brazilian Soil Classification System (SANTOS et al., 2018) and provide a cursory relationship with Soil Taxonomy (Figure 2).

SOC data

Database preparation

The assessment of current SOCS in Latossolos at a regional level required collecting data on soil C (SOC) content and soil bulk density (SBD) reported in published studies according to LULC − namely woodlands (MN), grasslands (CN) and cropland (LAV). Our study draws secondary data from surveys and published studies obtained by a systematic literature review. The latter involved an online search on the repositories Science Direct, Scielo, Web of Science, Biblioteca Digital de Teses e Dissertações using keywords (in Portuguese): native forest, native pasture, annual crops, crops, soil carbon, carbon storage, carbon stocks, carbon sequestration, soil carbon and Latosolos. The exclusion criteria used were pastures (non-native), other soil orders and studies carried out in Latossolos of Brazilian states. Data was obtained from 8 scientific articles, 18 theses, 4 dissertations, 20 technical reports. Additionally, 6 databases obtained from projects involving data collection campaigns were used, published from 1960 onwards on SOC and SBD, soil texture. SBD was lacking in 10 % of the selected studies. To estimate missing SBD data, we developed a model using multiple linear regression with the sampled sites with complete data; SBD = 0.8202404 + (0.0007072*clay) + (0.0008843*sand) - (0.0066852*SOC); R-squared: 0.3994 and P-value: < 0.00001.

Analitical methods

Organic C was analyzed by dry combustion in all samples of the primary dataset, whereas wet combustion methods (based on the original Walkley-Black – WB method) were used for most analyses in the secondary dataset. The latter method has been shown to underestimate SOC in comparison to dry combustiong. Given the variations of the WB data, we refrained from using a correction factor. DIECKOW et al. (2007) showed that this difference is around 5% in Argissolo Vermelho-Escuro (Argiudult) that is representative of soils of RS. All SOCS were calculated from the base data SOC and SBD retrieved from the selected studies according to TEIXEIRA et al. (2017): SOCS = SOC content (%) × layer thickness (m) × soil bulk density (Mg m^{-3}) x 100. The equivalent mass correction was not applied to cropland SOCS because only a few sampled sites had an adjacent reference SOCS measurement. Additionally, it was not possibible to ascertain if soil mass was conserved after conversion to cropland - erosion would have a confounding effect when reporting SOC stocks using mass corrections. Adionally, when data was reported by soil profile horizons (8 % of the data) that did not match the 0-30 and 0-100 cm reference depths, equal-area spline functions were applied to harmonize SOCS at the depths of interest, as described by BONFATTI et al. (2016). We used geoprocessing operations

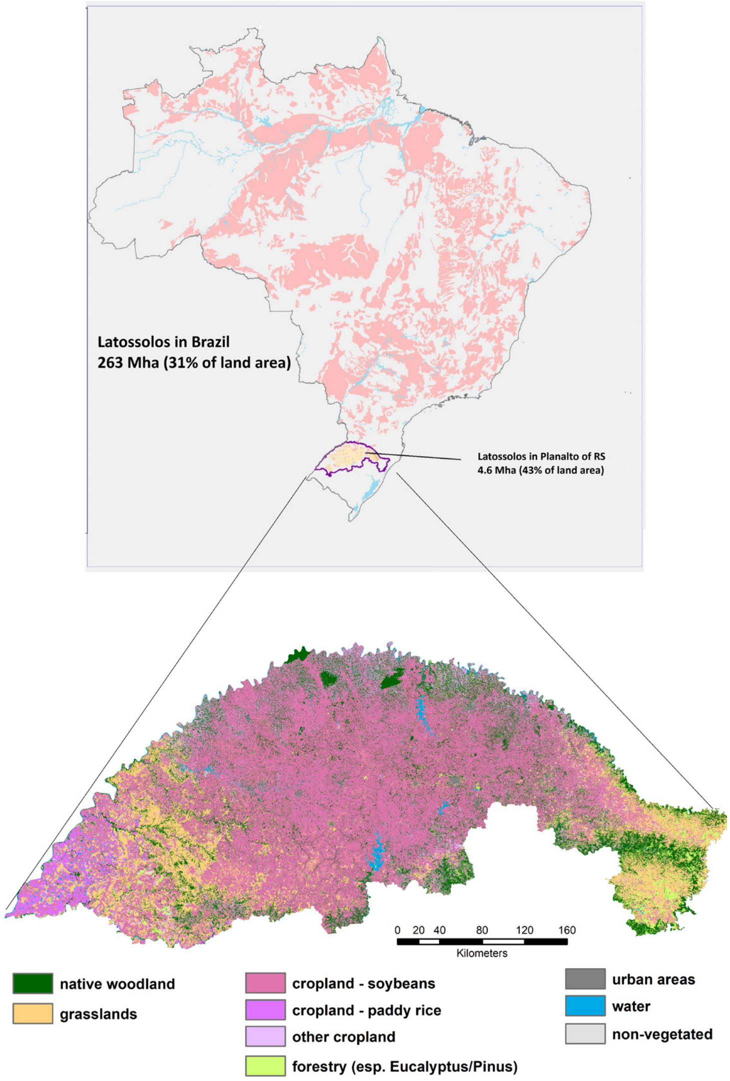

Figure 1 - Highlight of the study region on the Planalto in Rio Grande do Sul state, with general ocurrence of Latossolos (Oxisols) in Brasil (adapted from IBGE, 2023). Current land use/land cover according to MapBiomas v7 (2023)

conducted in ArcGIS (ESRI 2023) to estimate regional-scale SOC stocks in the Latossolos do Planalto. The state-wide soil map 1:250,000 (IBGE 2023) is freely distributed in vector format, comprising polygons that represent soil mapping units that have Latossolos as predominant soil class. SOCS were assigned to the attribute table of the digital map.

RESULTS

SOC data

The 195 published studies with maximum, minimum, and average values the SOCS in layers 0-30 cm and 0-100 cm, stratified by suborders/great groups of Latossolos according to SiBCS and land use are shown in table 1. The mean SOCS was compared with the IPCC default SOCS for “low-activity clays” in a warm temperate climate region (Figure 3).

The highest stocks were observed in the Latossolos Brunos (Table 2). These soils, which developed from basalt/rhyolite parent material, have high clay content (68% clay content on average), are deep, well-structured, and free draining. The high SOCS in these soils could be explained by the clayey texture as well as higher altitudes and precipitation and lower mean annual

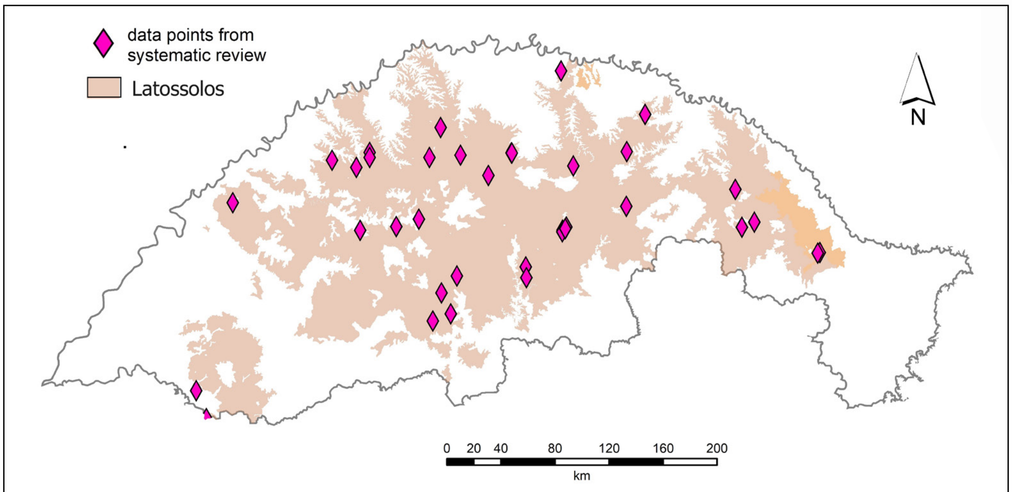

Figure 2 - Soil map of the Planalto, extracted from the RS map IBGE (2023). Soil classification presented at suborder level, according to SiBCS (5ed), grouped by major orders in Soil Taxonomy. Location of sample points obtained in the with SOC data and included in the dataset.

temperature where they occur (easternmost part of the Planalto).

High SOCS also were found in the most frequently occurring soil class in the Planalto, Latossolo Vermelho distroférrico-LVdf (25% of the Planalto), which has soil properties that are very similar to the Latossolos Vermelhos Aluminoférricos-LVdaf (4% of the soils in Planalto). Both contain Fe_2O_3 between 180 g kg^{-1} and 360 g kg^{-1} (topsoil to 100 cm depth), differing only by higher Al^{+3} (≥ 50%) in LVaf. Although, they are classified separately in the SiBCS, under undisturbed field conditions these soils behave very much alike: acidic, highly aggregated. Moreover, there were only a few studies (*n* = 12) reporting SOCS in LVaf, so that in table 1 we merged LVdf / LVdaf. Surprisingly, we found similar SOCS in the Latossolos Vermelhos Distróficos (LVd), soils that in this region have coarser texture (approximately 30% less clay than the other Latossolos in this study.

Table 1 - Soil organic C stocks Mg ha^{-1} (0-30 cm and 0-100 cm) in Latossolos, according to different land uses in the Planalto of RS.

Soil	LULC	------------------------0-30 cm------------------------					-------------------------0-100 cm-------------------------				
		n	max	min	mean	sd	*n*	Max	min	mean	sd
LBaf	woodland	1			123.8		1			229.1	
LBdf	grassland	4	112.5	86.5	98.5	12.3	4	267.4	182.3	237.2	38.7
LBdf	cropland	1			96.5						
LVaf	woodland	2	84.0	71.1	77.5	9.2					
LVaf	grassland	1			62.1		1			155.1	
LVaf	cropland	4	73.6	55.9	66.0	7.5	2	126.0	120.5	123.3	3.9
LVd	woodland	5	94.0	65.7	76.2	11.4	3	186.0	162.7	173.7	11.7
LVd	grassland	14	92.0	18.8	65.6	21.5	7	191.8	117.4	162.0	22.3
LVd	cropland	43	80.6	34.6	67.8	10.6	21	181.2	147.1	164.2	9.2
LVdf	woodland	16	113.3	49.3	71.1	16.7	2	166.2	111.4	138.8	38.8
LVdf	grassland	12	100.2	64.6	82.8	12.6	5	221.3	164.2	188.0	24.4
LVdf	cropland	41	98.5	370	65.6	12.7	5	237.0	112.3	164.7	47.9

LBaf: Latossolo Bruno aluminoférrico; LBdf: Latossolo Bruno distroférricos; LVaf: Latossolo Vermelho aluminoférrico; LVd Latossolo Vermelho distrófico; LVdf: Latossolo vermelho distroférrico; LU: Land Use.

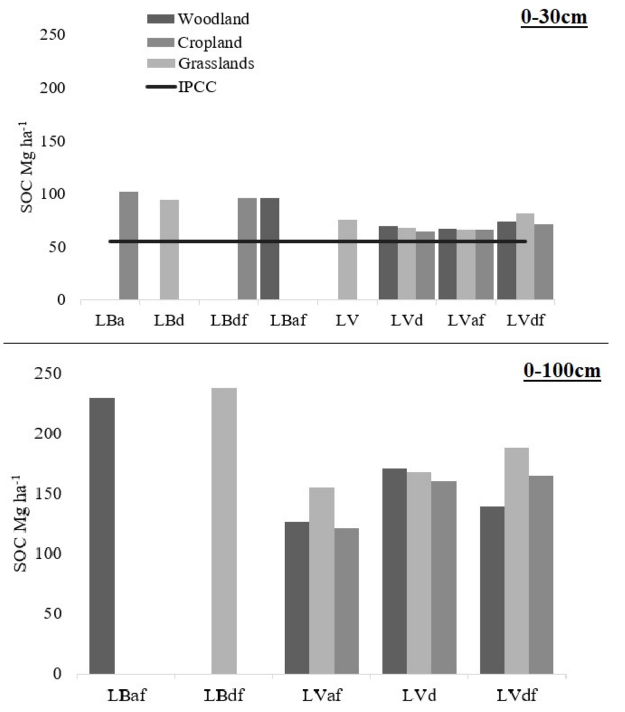

Figure 3 - Synthesis of SOCS (0-30 and 0 – 100 cm) by great groups of Latossolos and the IPCC default SOCS for low-activity clays soils. LBaf: Latossolo Bruno alumino férrico; LBdf: Latossolo Bruno distro férrico; LVaf: Latossolo Vermelho aluminoférrico; LVd: Latossolo Vermelho distrófico; LVdf: Latossolo Vermelho distroférrico. Line in 0-30 cm represents IPCC default value.

Regional extrapolation of SOC stocks

This compilation of legacy data and output from recent field studies SOCS in Latossolos was input in GIS environment to match soil and LULC maps to render a regional SOCS map to 30 cm depth (Figure 4). Using map algebra tools in GIS environment, we estimated total SOC stocks in Oxisols of the Planalto 419.9 Pg C. This estimate is 36% larger that our previous calculations of 308.3 Pg C (Table 2 in TORNQUIST et al., 2009).

Exploratory analysis of SOCS drivers

The integration of the soil orders, clay, sand, bulk density and SOCS (at 30 cm), land use (woodland, grassland, and cropland) and climatic variables (precipitation, elevation and temperature) was made in a PCA (Figure 5). This explained 68.2% of the data variability in the first two components, with a significance P = 0.001. The first component explained the 50.4%, grouped the variables such carbon stocks (SOCS30) precipitation, elevation and related them to the suborders Latossolo Bruno in the woodland, grassland, cropland land uses.

The second component explained the 17.8% of the variability of the data, related the clay and temperature variables with the Latossolos Vermelhos in woodland use (Figure 5). The most expressive accumulation of SOCS in the LB could be related to high elevation and higher precipitation. Abundant water availability promotes plant growth while lower temperature favors accumulation of soil organic matter. Additionally, the PCA did not reveal a high correlation between clay and SOCS. We further explored this in a regression analysis that revealed the same lack of correlation between clay and soil C stocks. The data obtained in this literature search encompassed soils with a wide textural range (100 - 800 g kg^{-1} clay). A lack of correlation between SOC with clay was foiund in other studies in Brazil (ZINN et al., 2005). We hypothesized that other drivers such vegetation and crops, elevation (114 - 963 m) and temperature

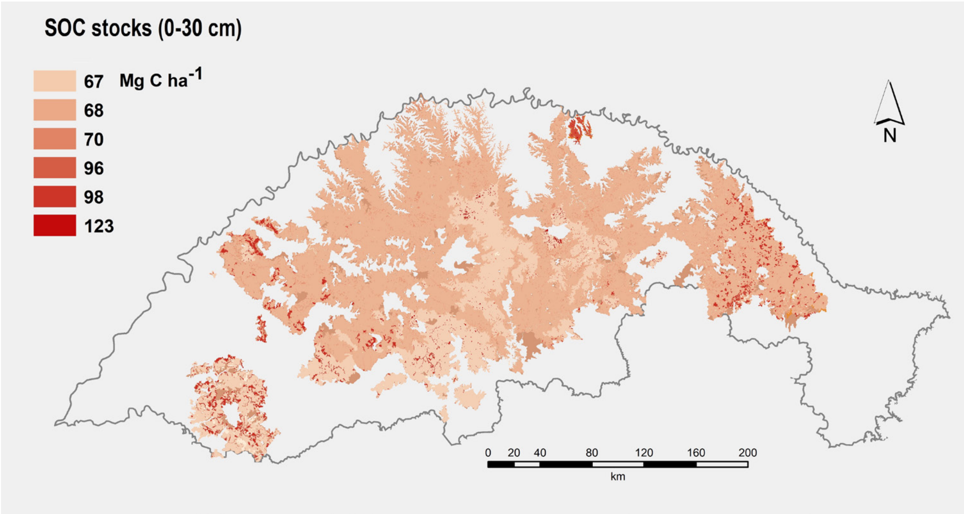

Figure 4 - Soil C stocks to 30 cm depth in Oxisols of the Planalto of Rio Grande do Sul.

(16 - 20 °C) affect more directly the C content in the soil than clay content.

Uncertainty and improvements

Uncertainty is inherent to SOCS accounting, especially when the dataset includes secondary and legacy data that compile a limited number of data points from SOCS studies. In this study, this was most evident for data deeper than 30 cm, which could be improved by sampling below 30 cm (BODDEY et al., 2010; EMBRAPA, 2014; IPCC, 2019). Another major issue with part of the data is the inherent inaccuracy

Table 2 - Mean SOCS Mg ha^{-1} in Latossolos in layers 0-30 cm and 0-100 cm from this study and comparison with other SOCS estimates.

Soil / Land Use	----------------This study----------------		BERNOUX et al. (2002)	IPCC[1] (2019)
	0-30cm	0-100 cm	0-30cm	
Latossolos				
Woodland	74 (± 19)	162 (± 38)	Woodland: 101 (± 7)	55 (± 4.4)
Grassland	79 (± 17)	187 (± 38)	Grasslands: 88 (± 6)	
Cropland	68 (± 12)	159 (± 32)		
Latossolo Bruno (LB)				
Woodland	124	229		
Grassland	98 (± 12.3)	237 (± 39)		
Cropland	96			
Latossolo Vermelho distroférricos/aluminoférrico (LVdf/LVaf)				
Woodland	74 (± 12.9)	132 (± 28.4)		
Grassland	72 (± 12.6)	182 (± 25.6)		
Cropland	66 (± 10)	157 (± 46.5)		
Latossolo Vermelho Distrófico (LVd)				
Woodland	76 (± 11.4)	171 (± 11.6)		
Grassland	66 (± 22)	167 (± 1.6)		
Cropland	68 (± 11)	161 (± 8.6)		

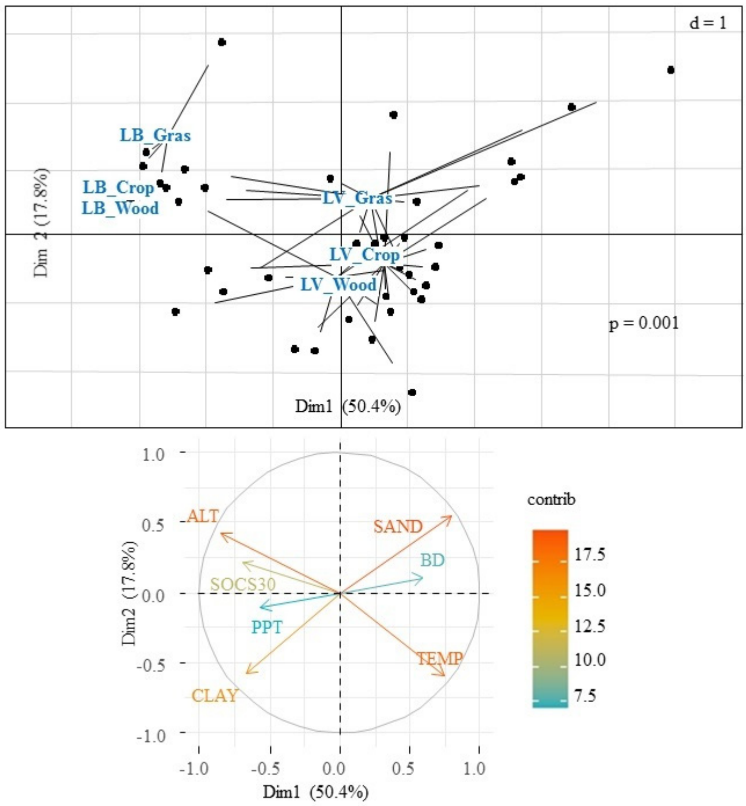

Figure 5 - Biplot of Principal Component Analysis with soil, land use and climate variables. LB_Grass: Latossolo Bruno Grasslands; LB_Crop: Latossolo Bruno Cropland; LB_Wood: Latossolo Bruno Woodland; LV_Grass: Latossolo Vermelho Grasslands; LV_Crop: Latossolo Vermelho Cropland; LV_Wood: Latossolo Vermelho Woodland; TEMP: temperature; PPT: prescipitation; ALT: elevation; BD: bulk density; SOCS30: Soil Organic Carbon Stocks at 0 – 30 cm layers.

of the Walkley-Black and its modifications (wet combustion C analytical methods) that were standard in the past, and usually underestimate C content (SKJEMSTAD et al., 2000; PEREIRA et al., 2006). The spatial extrapolation of SOCS based on a small-scale (1:250,000) soil map (Figure 3) also adds to the overall uncertainty, as it contains mapping units that are not exclusively Latossolos (i.e., are associations of soil classes); therefore, overestimating the true extent of this soil class and associated SOCS. Digital soil mapping techniques could help disaggregate these complex mapping units (SARMENTO et al., 2017), but this procedure would require an extensive collection of environmental covariates.

CONCLUSION

This study presents the most up-to-date dataset on SOC stocks of Latossolos, the most common soil of the Planalto of RS. The data obtained following existing protocols more rigorously than previous research, relying on several targeted SOC stock surveys. We concluded that, despite significant land use changes, soils of this region store large SOCS, 419.9 Pg C, 36% higher than previously estimated. Our findings indicated large SOC in Latossolos (to a 30 cm depth), especially at higher altitudes in the eastern part of the Planalto. Cropland soils had lower overall SOC, but our study design does not warrant robust comparisons with native vegetation, which would ideally employ paired-site sampling approaches.

ACKNOWLEDGEMENTS

This study and its publication were supported by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) graduate program grants and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq). Cristhian Hernandez Gamboa was supported by a postdoc fellowship from

Fundação de Apoio à Universidade de São Paulo (FUSP), as a part of the Nature Based Solutions (NBS) project in the Research Center Green House Gas Innovation (RCGGI) (Escola Politecnica/USP).

DECLARATION OF CONFLICT OF INTEREST

We wish to confirm that there are no known conflicts of interest associated with this publication. There has been no significant financial support for this research that could have influenced in the design of the study, in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

AUTHORS' CONTRIBUTIONS

Conceptualization: Ana Caroline Messias de Magalhães, Carlos Gustavo Tornquist. Data acquisition: Ana Caroline Messias de Magalhães and Cristhian Hernandez Gamboa. Design of methodology and data analysis: Ana Caroline Messias de Magalhães, Cristhian Hernandez Gamboa and Carlos Gustavo Tornquist. Carlos Gustavo Tornquist and Cristhian Hernandez Gamboa prepared the draft of the manuscript. All authors critically revised the manuscript and approved of the final version.

DATA AVAILABILITY

All data are available in the FigShare repository (https://doi.org/10.6084/m9.figshare.25058504.v1).

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